SOCIETY. INTEGRATION. EDUCATION
Proceedings of the International Scientific Conference. Volume IV, May 24th -25th, 2019. 134-143

GAIT PARTITIONING WITH SMART SOCKS SYSTEM

Peteris Eizentals
Institute of Biomedical Engineering and Nanotechnologies, Riga Technical University, Latvia

Aleksejs Katashev
Institute of Biomedical Engineering and Nanotechnologies, Riga Technical University, Latvia

Aleksandrs Oks
Institute of Design and Technology, Riga Technical University, Latvia

Abstract. *Gait is a very complex movement, involving the central nervous system and a significant part of the skeletomuscular system. Any disease that is affecting one or more of the involved parts will reflect in the gait. Therefore, gait analysis has been studied extensively in the context of early disease diagnostics, post-operation rehabilitation monitoring, and sports injury prevention. Gait cycle phase partitioning is one of the most common gait characteristic analysis methods, which utilizes the cyclical nature of human gait. Pressure sensitive mats and insoles are considered the gold standard, but some inherent limitations of these methods urge researchers to seek for alternatives. One of the proposed alternatives is Smart Sock systems, which contain textile pressure sensors. The main limitation of Smart Sock systems is the limited number of sensors, thus complicating gait phase partitioning by these systems. The present paper describes gait phase partitioning using plantar pressure signal obtained by a Smart Sock system. Six-phase partitioning was achieved, including such gait phases as initial contact, loading response, mid stance, terminal stance, pre-swing and swing phase. Mean gait cycle time values obtained from the experimental data were in accordance with the ones found in the literature.*
Keywords: *gait analysis; gait phase partitioning; Smart socks.*

Introduction

Human gait is a complex movement involving almost all body, including skeletal, muscle and neural systems. Any problem with one of the involved systems could affect the gait, and, therefore, the gait can be used for analyzing the performance of the body in sport (Santuz, Ekizos, & Arampatzis, 2015) and medicine. In medicine gait analysis has been used for post-surgery recovery evaluation (Selles, Formanoy, Bussmann, Janssens, & Stam, 2005) and for early detection and evaluation of such diseases as Parkinson disease (Mileti et al., 2017), multiple sclerosis, cerebral palsy (Zhang, Lu, Uswatte, Taub, & Sazonov, 2014), and gait pathologies (Chen, Huang, & Xu, 2008). Gait partitioning is a

http://dx.doi.org/10.17770/sie2019vol4.3844

widely accepted gait feature analysis and evaluation method that analyses the gait by separating the gait cycle in several functional phases. The number of phases can vary from two (stance and swing phase) to up to eight phases, namely initial contact, loading response, mid stance, terminal stance, pre-swing, initial swing, mid swing and terminal swing (Taborri, Palermo, Rossi, & Cappa, 2016).

Much research has been done for developing different methods of gait partitioning. Force sensing mats and pressure insoles are considered the golden standard due to the accuracy of the measurement they provide, however, lately in the majority of studies accelerometers, gyroscopes and inertial measurement units (IMUs) have been employed (Taborri et al., 2016). This is due to the relatively high cost of the former, which makes them unsuitable for adoption in small clinics or for personal use. On top of that, limitations such as small active area and strictly indoor application of force sensing mats, and impact on the gait measurement for sensing insoles (Kong & De Heer, 2009) encourage researchers to explore other tools. Accelerometers, gyroscopes, and IMUs, alone or in combination, constitute nearly 70% of all research in the field, with the majority of the remaining being optoelectronic systems, foot switches and pressure insoles (Taborri et al., 2016). Accelerometer, gyroscope, and IMUs based systems, however, require rather accurate positioning on the body or a special calibration procedure to decrease the positioning error as the result is calculated from known sensor positions in space (Taborri et al., 2016). Moreover, these sensors, if not well attached, could shift the position during an impact movement such as running. On top of that, several sensors have to be placed on the body for best performance, thus greatly increasing the complexity of positioning.

Smart Socks system is a relatively new approach to gait analysis and is not yet widely used in clinical practice. Smart Socks system contains several smart textile pressure sensors incorporated directly in the socks during the manufacturing process from roughly the same material as the rest of the sock. Such systems are relatively cheap and simple to manufacture but they lack readily available methods for clinical use. It can be considered a simplified version of pressure sensitive insoles, where the limitations have been solved at the expense of decreased sensor count and resolution. The main disadvantage, however, is the absence of methods for analysis of the plantar pressure obtained by these systems.

This paper presents a method for gait cycle partitioning by application of plantar pressure measurement obtained by Smart Socks system. Six-phase partitioning was achieved, including initial contact, loading response, mid stance, terminal stance, pre-swing, and swing. The partitioning is limited to six phases due to the fact that swing sub-phases cannot be distinguished with plantar pressure measurement systems alone as that requires information about knee flection and the angle of the tibia with respect to the ground (Joshi, Lahiri, & Thakor, 2013). An experiment was performed to verify the feasibility of the developed method, where the plantar pressure measurement was obtained for three participants during normal gait. Gait partitioning was applied to the obtained measurement and the result was compared to the standard values obtained from the literature. Full gait partitioning algorithm description is given in this paper and the results and their implications are discussed.

Materials and Methods

This paper presents a novel gait partitioning method using smart socks system. According to this method, first, the plantar pressure of the foot while walking is obtained by textile sensors. Then the measurement is processed to recognize individual steps and extract temporal parameters, and finally, the gait phase information is calculated from the measurement.

Hardware

Smart Socks system used in this study contains five textile pressure sensors that are incorporated directly into the socks during the manufacturing process from special conductive yarns, two sensors under the heel, one sensor in the lateral side of mid-foot and two sensors under the metatarsus (Fig. 1). These conductive yarns create loops that are forced together when an external pressure on the sensor is created thus generating electric shortcuts in the sensor, which in turn lower the electrical resistance of the sensor. As a result, the conductivity of a textile sensor is directly proportional to the applied pressure on the sensor. The conductive lines in the sock, which link sensors with the contacts, were produced of the second type of conductive yarn that has lower electrical resistance compared to the yarn that was used for sensor manufacturing.

Figure 1 ***Smart Socks system with 5 textile sensors***

Snap connectors were attached to the end of the connecting lines on the lateral side above the ankle for electrical connections of the data acquisition box (Fig. 2). The data acquisition box measured the resistance of textile sensors through a voltage divider circuit at approx. 25Hz rate and sent it to the computer through a Bluetooth connection, where it was received, synchronized, interpolated to 40 samples per second and saved to a file by a dedicated program made in LabVIEW. Post-processing of the saved measurement was performed in Matlab.

Figure 2 ***Smart Socks system with the data acquisition box***

Data Processing

Gait phase partitioning in this study was performed in Matlab software according to the following algorithm. First, the measurement from each sensor was filtered with a zero-phase digital low pass filter to remove any noise present in the signal. Next, local normalization was performed for each signal according to the equation:

$$u_i' = \frac{u_i - \min\limits_{a \le i \le b} u_{[a,b]}}{\max\limits_{a \le i \le b} u_{[a,b]} - \min\limits_{a \le i \le b} u_{[a,b]}}, \tag{1}$$

where u_i – the *i*-th measurement
a – the first index of the normalisation window
b – the last index of the normalisation window

Normalization is required to eliminate the difference in sensitivity between sensors. Sensitivity variation between sensors is an inevitable limitation of textile sensors, which results from the materials used in the manufacturing process and the variability of the manufacturing itself. This, however, was not a significant issue for this respective application as only temporal parameters are required for gait phase partitioning. After normalization, the average of the signal from two sensors located on the heel was calculated and assigned to a new signal describing the pressure variation on the heel, while the same was done for two metatarsal sensors to produce a signal for the pressure variation under the toe. These two signals were employed for gait phase partitioning.

The six calculated phases included the initial contact, loading response, mid stance, terminal stance, pre-swing, and swing phase (Fig. 3). The initial contact is the moment when the foot of reference, for which the parameter is calculated, contacts the ground. In normal walking gait, this initial contact is done by the heel, although entire foot or toe contact can happen in patients with pathological gait pattern. According to the gait partitioning algorithm described in this study, the initial contact time is registered, when the combined heel signal value falls below the threshold value, which was selected 0.5 (from trial and error) (Fig. 4).

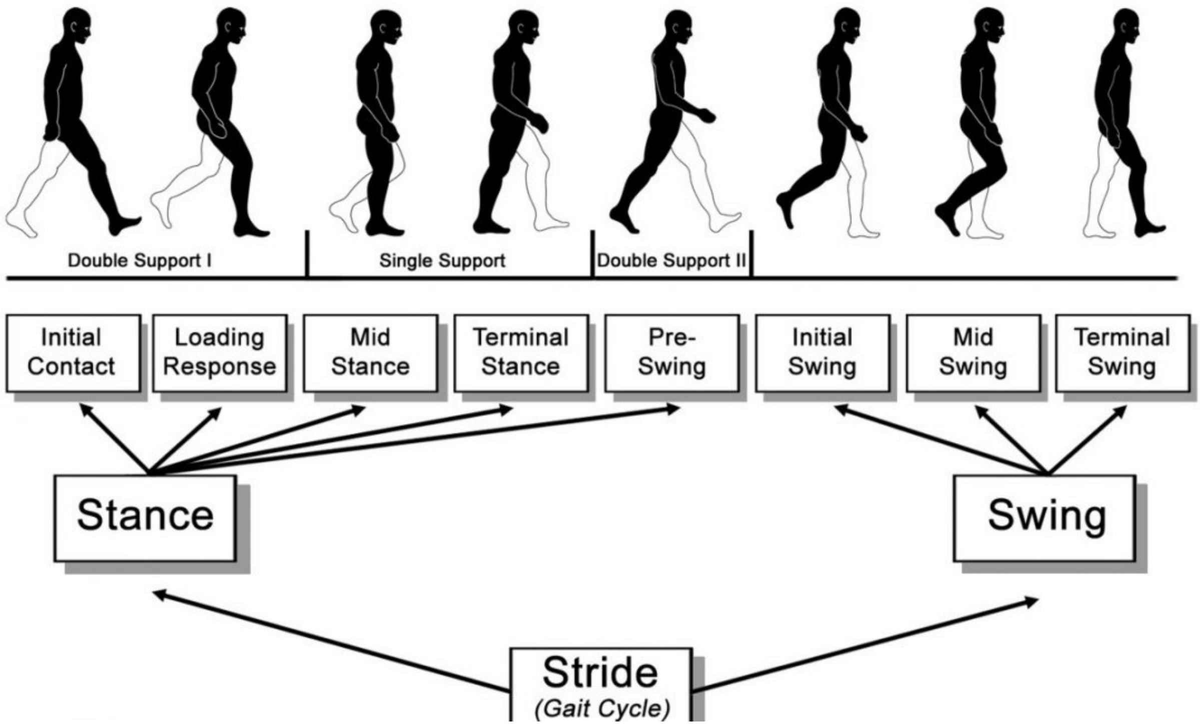

Figure 3 ***Phases of the gait cycle***
(Stöckel, Jacksteit, Behrens, Skripitz, Bader, & Mau-Moeller, 2015)

The loading response (LR) begins with the initial contact of the reference foot and concludes with the contralateral toe off moment. Toe off moment in this study was calculated as the moment when the combined toe signal raised above a threshold of 0.7 (from trial and error).

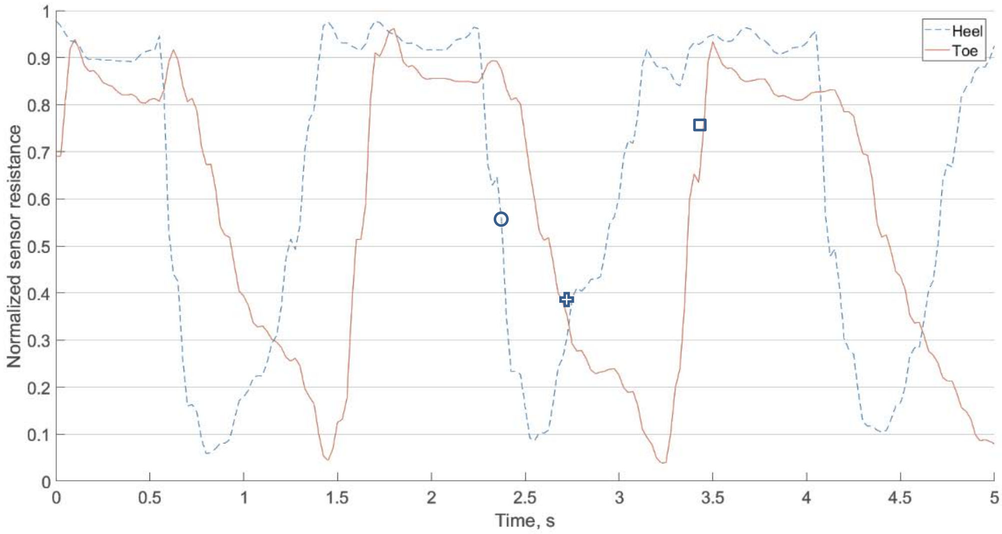

Figure 4 ***Sensor signal example, heel touch (circle), flat foot (cross) and toe raise (square) detection moments are shown***

The mid-stance (MS) phase begins with the contralateral toe off moment and concludes with the moment when the center of gravity is directly above the reference foot. In this study, the endpoint of this phase was assumed to be the moment when the toe signal and the heel signal were closest in value, as it is the moment when the pressure moves from the heel region to the metatarsus and toes.

The terminal stance (TS) begins with the center of gravity above the reference foot and concludes with the contralateral heel contact with the ground or initial contact. Finally, the pre-swing (PS) phase lasts from the contralateral initial contact until the toe rise of the reference foot from the ground. As it can be seen, all five stance phases are calculated from three temporal events of each foot, namely heel strike, flat foot and toe off, but measurements from both feet are required for gait phase partitioning.

Results and Discussion

A gait partitioning method for gait phase calculation has been proposed in the present study that uses feet plantar pressure measurement, obtained by Smart Socks system. An experiment was performed for evaluation of the feasibility of the proposed method, where the plantar pressure of three participants was acquired with the Smart Socks system described above and processed according to the proposed method. Each participant used two types of shoes, casual and sports shoes, to analyze the effect of the footwear on the measurement. The difference between casual and sports shoes typically is in the shape and material, where sports shoes generally are more conforming to the foot, with one of the major differences being a more prominent supinator, which supports the foot and puts extra pressure on sensors. The summary of the measurement is given in the table below (Table 1) together with the range of typical values for each phase found in the literature (Perry & Burnfield, 2010).

Table 1 **Experimental result, mean percentage of the phase from the total gait cycle and the standard deviation, the number after the dot for volunteer number means casual (1) or sports shoes (2)**

Left foot													
Volunt.	Number of steps	Loading response		Midstance		Terminal stance		Pre-swing		Stance		Swing	
		% of the full step		% of the full step		% of the full step		% of the full step		% of the full step		% of the full step	
		mean	std	mean	std	mean	std	mean	std	mean	std	mean	std
1.1	25	12.39	1.67	18.78	6.63	17.29	6.09	14.55	3.70	62.83	2.49	37.17	2.49
1.2	21	11.20	2.05	15.50	5.00	19.96	5.38	14.47	1.83	61.12	1.66	38.88	1.66
2.1	88	8.59	2.15	20.10	6.46	18.41	7.13	12.63	2.04	59.74	2.28	40.26	2.28
2.2	78	8.75	2.05	26.36	5.37	12.55	5.45	12.83	1.98	60.49	2.00	39.51	2.00
3.1	24	3.07	1.20	15.80	4.08	29.36	4.03	6.71	0.97	54.93	1.81	45.07	1.81
3.2	42	6.55	2.20	16.31	4.82	21.77	6.00	12.88	1.93	57.52	3.95	42.34	3.06
Right foot													
1.1	25	14.20	1.29	14.26	5.38	22.99	6.00	12.45	1.59	63.90	2.09	36.10	2.09
1.2	21	14.25	1.79	16.05	6.99	22.95	7.53	11.22	2.02	64.46	1.62	35.54	1.62
2.1	88	12.59	2.05	19.01	7.87	21.26	8.12	8.65	2.19	61.51	2.46	38.49	2.46
2.2	78	12.82	1.95	24.83	6.31	14.65	6.21	8.86	2.01	61.15	1.93	38.85	1.93
3.1	24	6.37	1.19	16.75	4.13	28.14	4.98	3.06	1.22	54.33	2.79	44.94	1.66
3.2	42	12.86	1.83	20.15	5.00	22.24	5.02	6.58	2.22	61.83	2.92	38.10	2.45
Reference		10-12%		18-20%		18-20%		10-12%		60-62%		38-40%	

It should be noted that the typical value range has only suggestive nature as it is widely recognized that there is a significant difference between individuals and even feet of the same person due to the asymmetry (Herzog, Nigg, Read, & Olsson, 1989). The results for each participant individually are also depicted in Fig. 5.

From the data given in the table, it can be seen that the stance phase time is in a close agreement with the expected 60% of the full gait cycle. The exception is participant 3 with casual shoes (Table 1, entry 3.1), which could be explained by poor placement of socks on feet. This is further supported when analyzing this particular measurement phase by phase. As can be seen, loading response and pre-swing values are significantly lower than normal, which could be caused by sensor shift in dorsal (heel) direction. This is a typical problem when putting on shoes, which makes the sock to be pulled more on the foot, thus altering the placement of sensors.

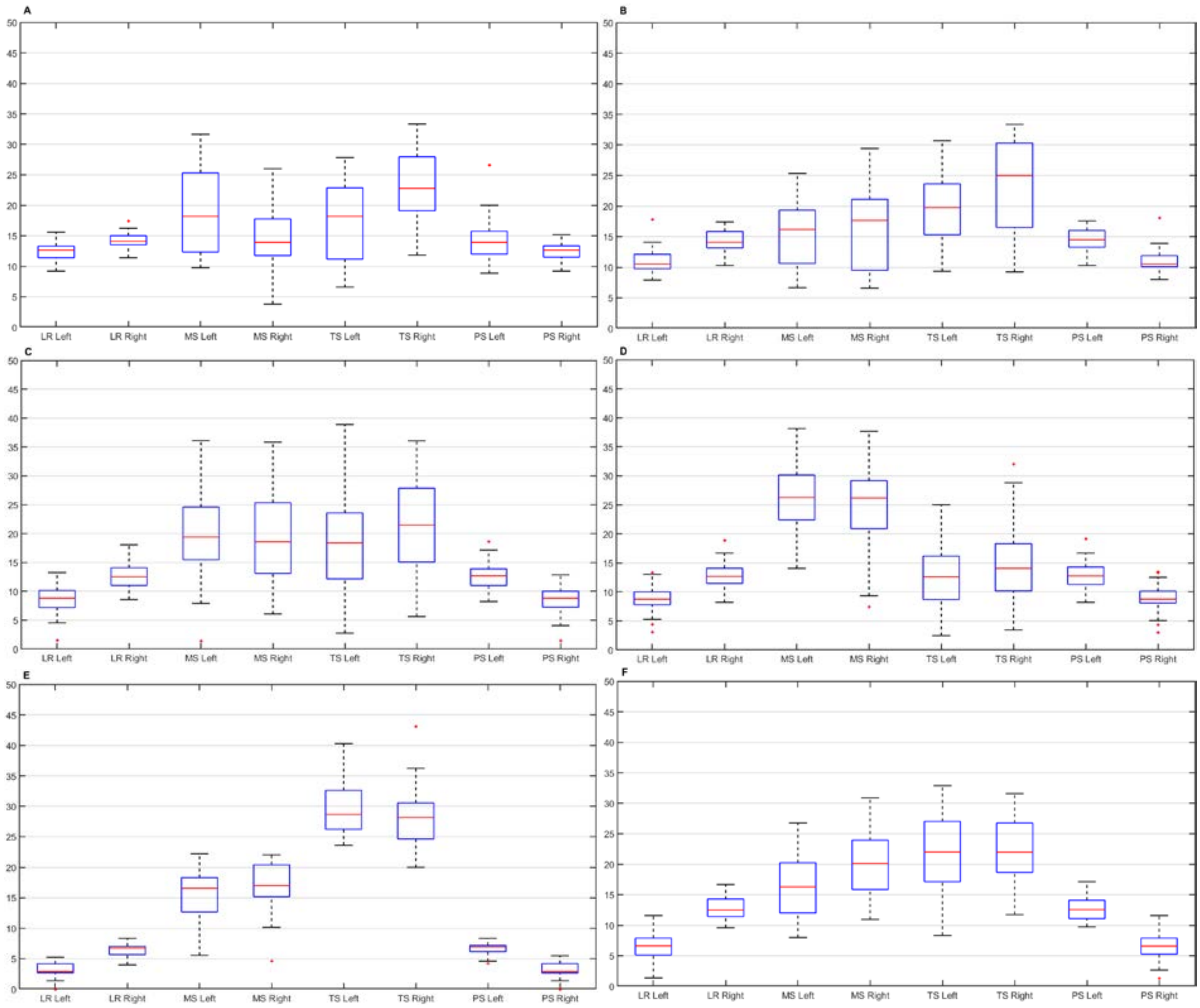

Figure 5 ***The calculated percentage of the full step for each phase (figures A, B, C, D, E and F correspond to Table 1 rows 1.1, 1.2, 2.1, 2.2, 3.1 and 3.2 respectively, left column – casual shoes, and right column – sport shoes)***

As it can be seen from the data in Table 1, the difference between measurement with casual and sports shoes for the first two participants was rather low for the double support phases (loading response and pre-swing), and for the total stance phase time. On the other hand, the highest variance was for the midstance and terminal stance phases. These two phases are separated by the moment of foot-flat when the center of mass is directly above this foot. In the developed algorithm, this moment is detected when the signal from front sensors (toe pressure signal) is closest to the signal from rear sensors (heel pressure signal). In sports shoes, the pressure on sensors can be affected by the supinator, and therefore the foot-flat moment is not exactly when the signals of front and back are equal.

A considerable step to step variation in separate phase result can be seen in Fig. 5. Although this is to be expected, considering the nature of walking and keeping the balance, care should be taken when analyzing separate steps. The greatest variance was observed for the midstance phase and terminal stance phase also called the single support phases. The sum of these phases has a significantly lower difference between shoe types than if these phases are compared separately (approx. 0.4-1.7% for combined single support phase compared to up to 1.8-12.4% for the sum of separate phase difference). Therefore, the calculation of the moment for foot-flat must be improved by additional information, such as the signal from the fifth sensor or by using the Step Vector algorithm developed by the authors of this article previously especially for Smart Socks systems.

A significant cause for error in the calculation can be a low sampling rate for the measurement. The sampling rate for data used in this study was 40 samples per second, with 25ms time between two measurements. This means that a single sample error can give up to 2.5% error to the calculation of the time for an event if the full step cycle is 1s or even more for shorter steps. This issue can be solved by using faster data acquisition electronics.

Conclusions

This paper presented a novel gait partitioning method using Smart Socks system. To evaluate the proposed method, plantar pressure measurement for normal walking gait was obtained for three participants. The experiment was performed with two type footwear, casual shoes, and sports shoes to evaluate the effect of the footwear on the measurement. Despite the limited sampling rate and other possible error sources, such as the position of socks on the foot during the experiment, calculated gait phase parameters in most cases were in accordance or close to the values found in the literature.

For future work, additional study is necessary to compare findings with an established reference. This future study will be performed with improved electronics to achieve a better sampling rate and a wider population sample.

Acknowledgments

This work has been supported by the European Regional Development Fund within the Activity 1.1.1.2 “Post-doctoral Research Aid” of the Specific Aid Objective 1.1.1 “To increase the research and innovative capacity of scientific institutions of Latvia and the ability to attract external financing, investing in human resources and infrastructure” of the Operational Programme “Growth and Employment” (No. 1.1.1.2/VIAA/1/16/153).

References

Herzog, W., Nigg, B.M., Read, L.J., & Olsson, E. (1989). Asymmetries in ground reaction force patterns in normal human gait. *Medicine & Science in Sports & Exercise, 21*(1), 110–114. DOI: 10.1249/00005768-198902000-00020

Joshi, C.D., Lahiri, U., & Thakor, N.V. (2013). Classification of gait phases from lower limb EMG: Application to exoskeleton orthosis. *2013 IEEE Point-of-Care Healthcare Technologies (PHT).* DOI:10.1109/pht.2013.6461326

Kong, P.W., & De Heer, H. (2009). Wearing the F-Scan mobile in-shoe pressure measurement system alters gait characteristics during running. *Gait & Posture, 29*(1), 143–145. DOI:10.1016/j.gaitpost.2008.05.018

Chen, M., Huang, B., & Xu, Y. (2008). Intelligent shoes for abnormal gait detection. *2008 IEEE International Conference on Robotics and Automation.* DOI:10.1109/robot.2008.4543503

Mileti, I., Germanotta, M., Alcaro, S., Pacilli, A., Imbimbo, I., Petracca, M., & Palermo, E. (2017). Gait partitioning methods in Parkinson's disease patients with motor fluctuations: A comparative analysis. *2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA).* DOI:10.1109/memea.2017.7985910

Perry, J., & Burnfield, J.M. (2010). *Gait Analysis: Normal and Pathological Function*. New York, NY: Slack Inc

Santuz, A., Ekizos, A., & Arampatzis, A. (2015). A Pressure Plate-Based Method for the Automatic Assessment of Foot Strike Patterns During Running. *Annals of Biomedical Engineering*, *44*(5), 1646–1655. DOI: 10.1007/s10439-015-1484-3

Selles, R.W., Formanoy, M.A.G., Bussmann, J.B.J., Janssens, P.J., & Stam, H.J. (2005). Automated Estimation of Initial and Terminal Contact Timing Using Accelerometers; Development and Validation in Transtibial Amputees and Controls. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13*(1), 81–88. DOI:10.1109/tnsre.2004.843176

Stöckel, T., Jacksteit, R., Behrens, M., Skripitz, R., Bader, R., & Mau-Moeller, A. (2015). The mental representation of the human gait in young and older adults. *Frontiers in Psychology, 6.* DOI:10.3389/fpsyg.2015.00943

Taborri, J., Palermo, E., Rossi, S., & Cappa, P. (2016). Gait Partitioning Methods: A Systematic Review. *Sensors, 16*(1), 66. DOI:10.3390/s16010066

Zhang, T., Lu, J., Uswatte, G., Taub, E., & Sazonov, E.S. (2014). Measuring gait symmetry in children with cerebral palsy using the SmartShoe. *2014 IEEE Healthcare Innovation Conference (HIC)*. DOI:10.1109/hic.2014.7038871